

# Lecture 2: Quenching

## Plan

- the quench process
- decay times and temperature rise
- propagation of the resistive zone
- resistance growth and decay times
- quench protection schemes
- case study: LHC protection



# Magnetic stored energy

## Magnetic energy density

$$E = \frac{B^2}{2\mu_0} \quad \text{at 5T} \quad E = 10^7 \text{ Joule.m}^{-3} \quad \text{at 10T} \quad E = 4 \times 10^7 \text{ Joule.m}^{-3}$$

## LHC dipole magnet (twin apertures)

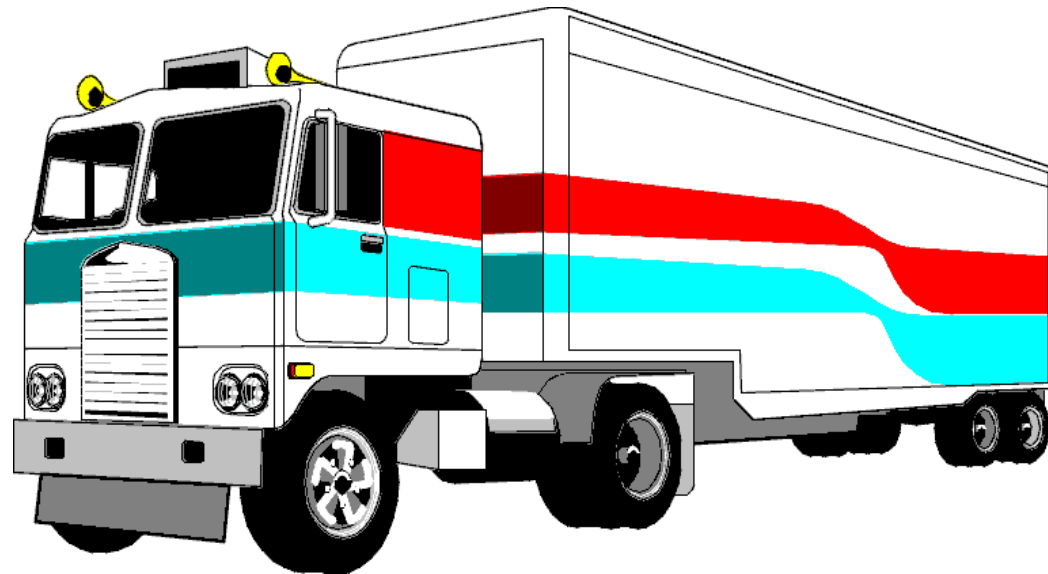
$$E = \frac{1}{2}LI^2 \quad L = 0.12\text{H} \quad I = 11.5\text{kA}$$

$$E = 7.8 \times 10^6 \text{ Joules}$$

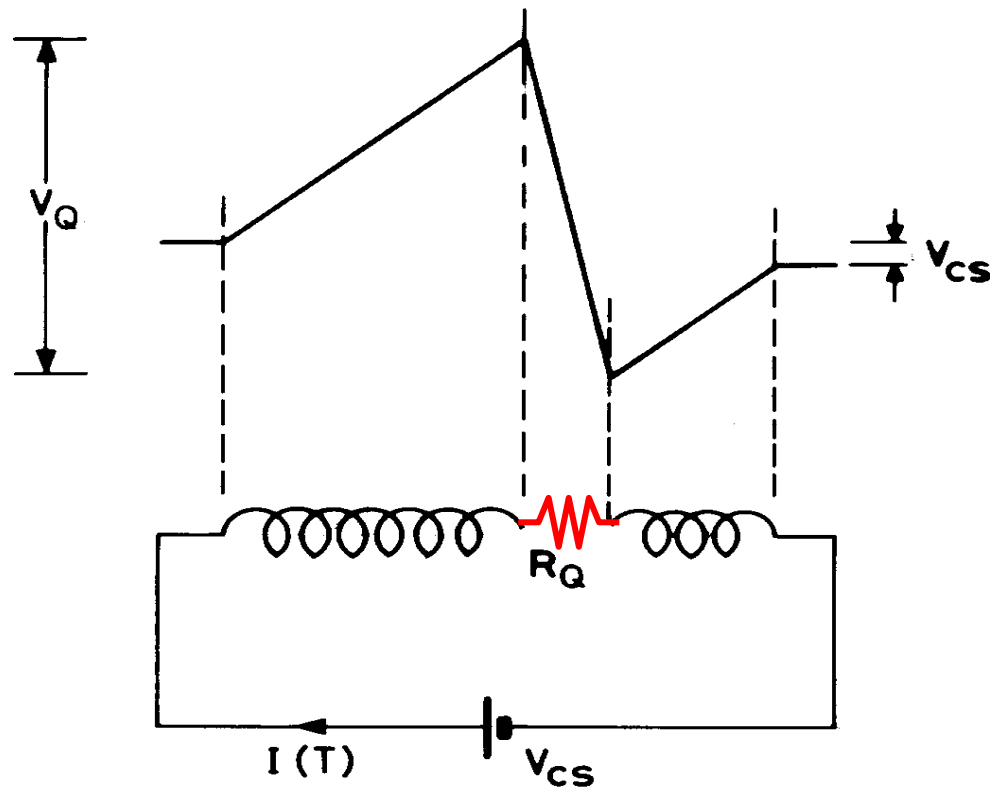
the magnet weighs 26 tonnes

so the magnetic stored energy is equivalent to the kinetic energy of:-

**26 tonnes travelling at 88km/hr**



# The quench process



- resistive region starts somewhere in the winding at a **point**  
- **this is the problem!**
- it grows by thermal conduction
- stored energy  $\frac{1}{2}LI^2$  of the magnet is dissipated as heat
- greatest integrated heat dissipation is at point where the quench starts
- internal voltages much greater than terminal voltage ( $= V_{cs}$  current supply)
- maximum temperature may be calculated from the current decay time via the  $U(\theta)$  function (adiabatic approximation)

# The temperature rise function $U(\theta)$

or the 'fuse blowing' calculation  
(adiabatic approximation)

$$J^2(T)\rho(\theta)dT = \gamma C(\theta)d\theta$$

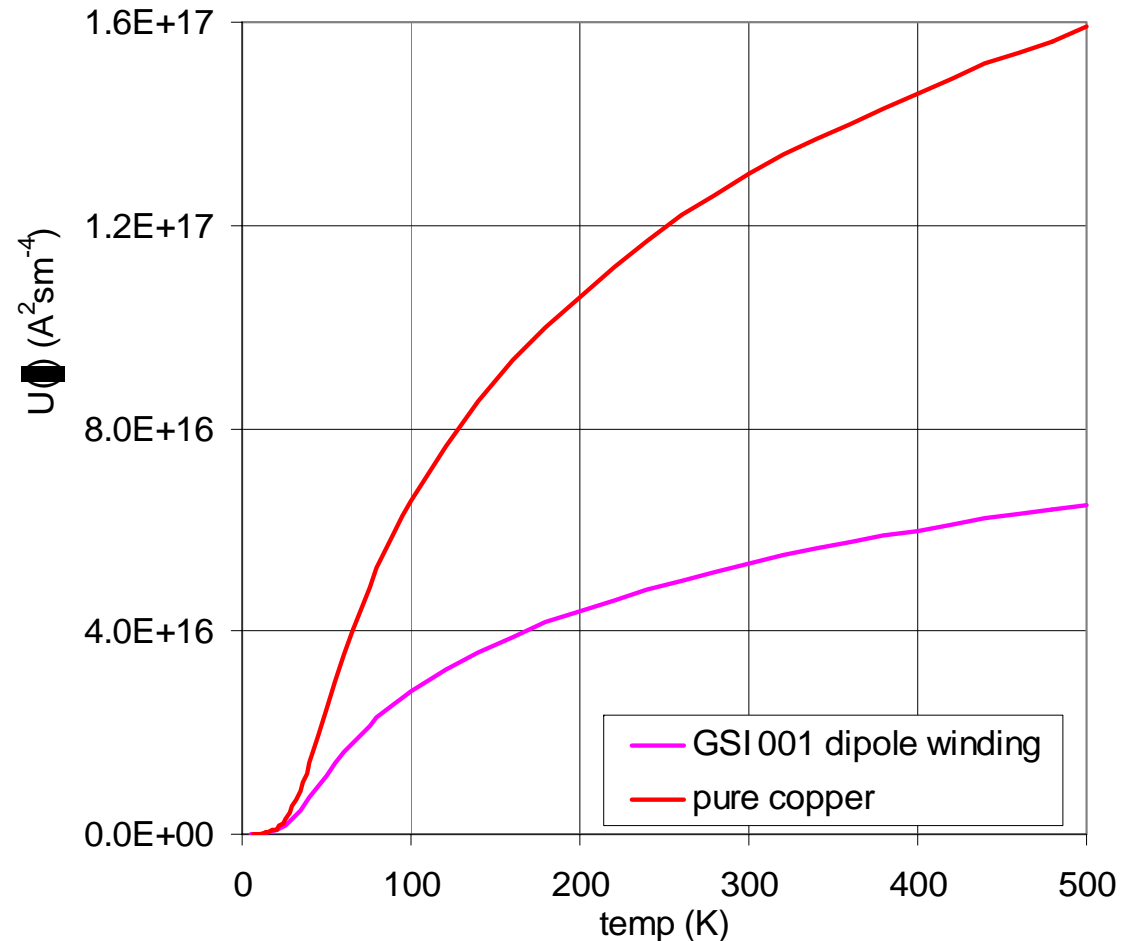
$J(T)$  = overall current density,  
 $T$  = time,  
 $\rho(\theta)$  = overall resistivity,  
 $\gamma$  = density,  $\theta$  = temperature,  
 $C(\theta)$  = specific heat,  
 $T_Q$  = quench decay time.

$$\int_0^\infty J^2(T) dT = \int_{\theta_0}^{\theta_m} \frac{\gamma C(\theta)}{\rho(\theta)} d\theta$$

$$= U(\theta_m)$$

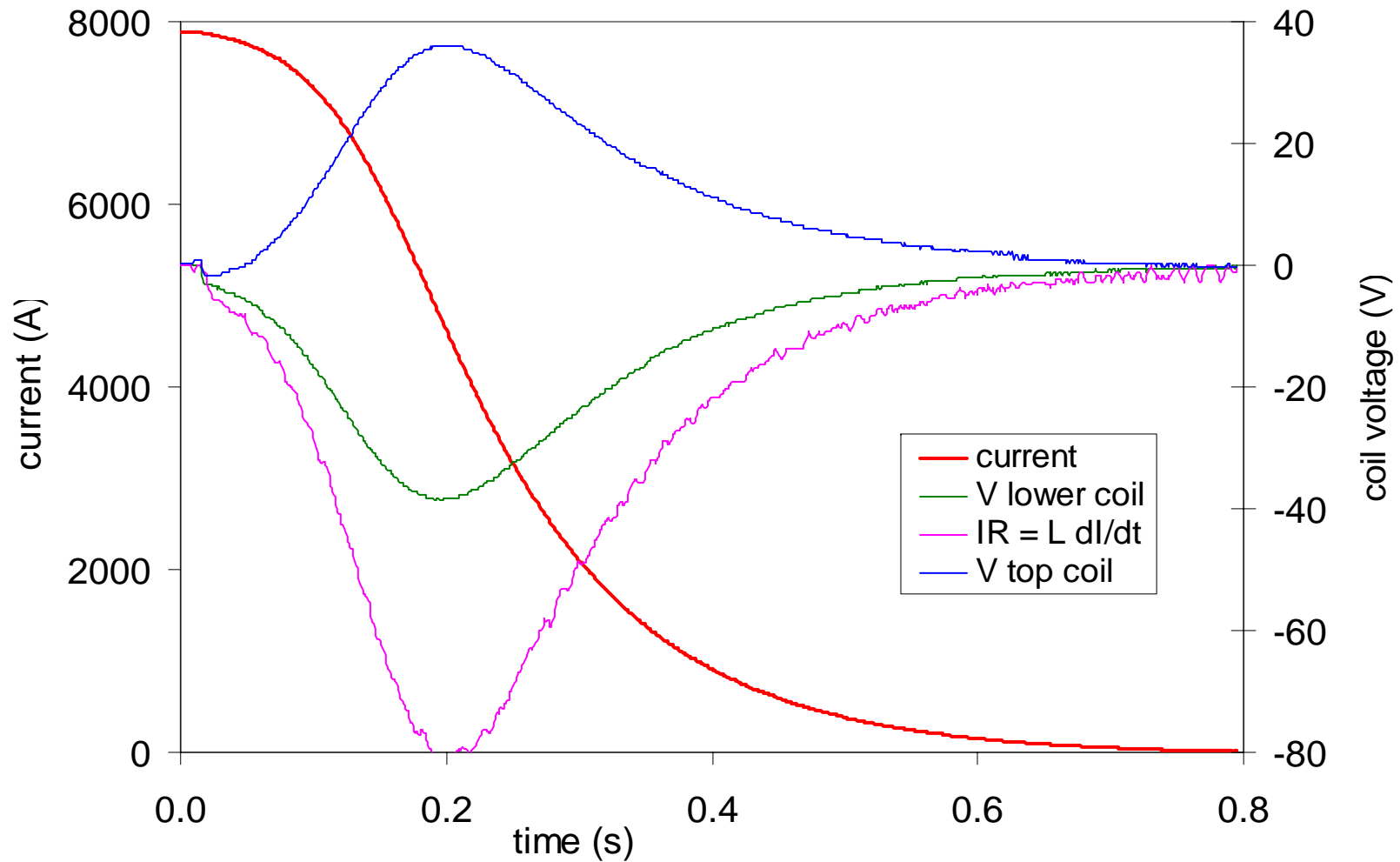
$$J_o^2 T_Q = U(\theta_m)$$

- GSI 001 dipole winding is  
 50% copper, 22% NbTi,  
 16% Kapton and 3% stainless steel



- NB always use **overall** current density

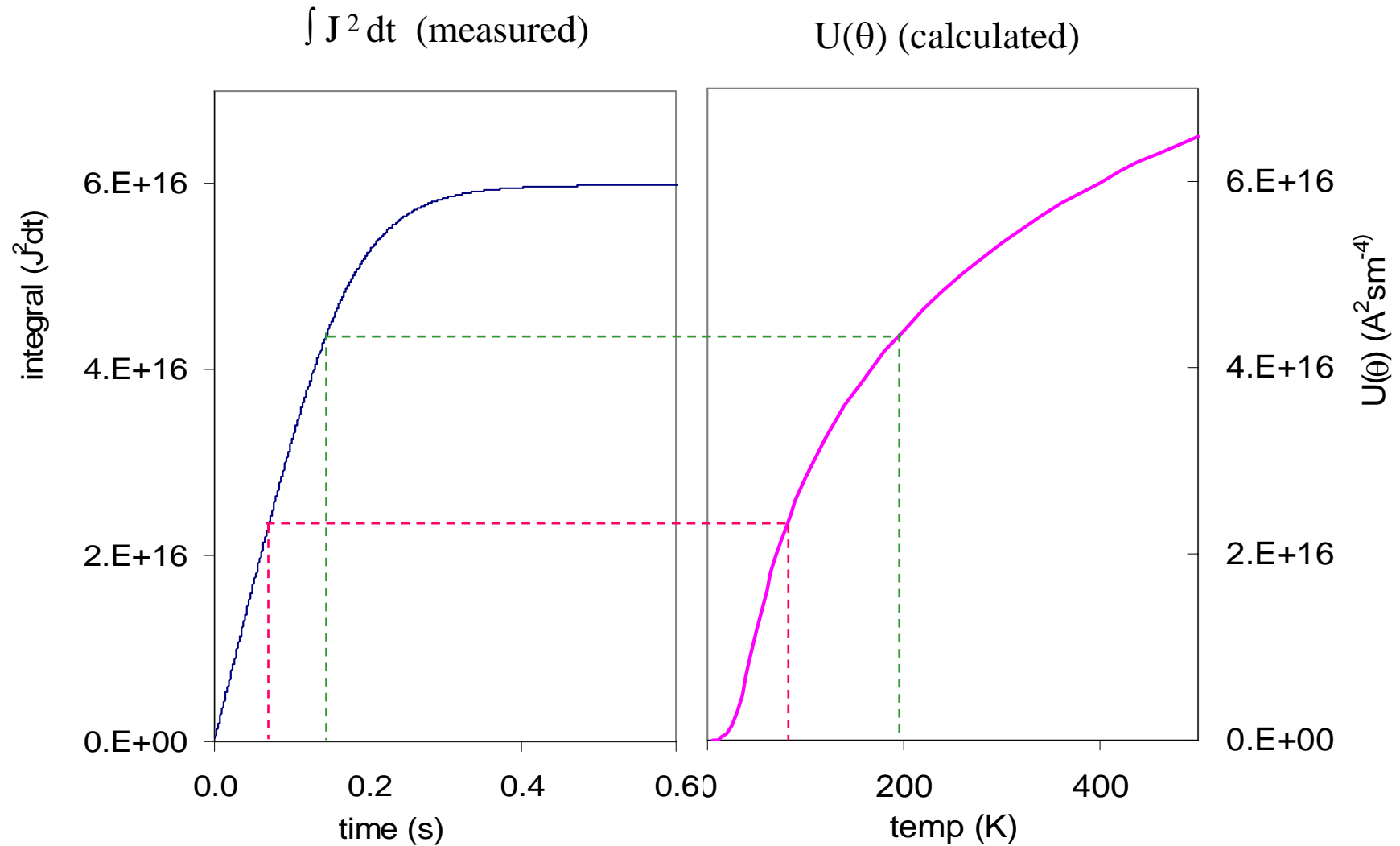
# Measured current decay after a quench (with calculated voltages)



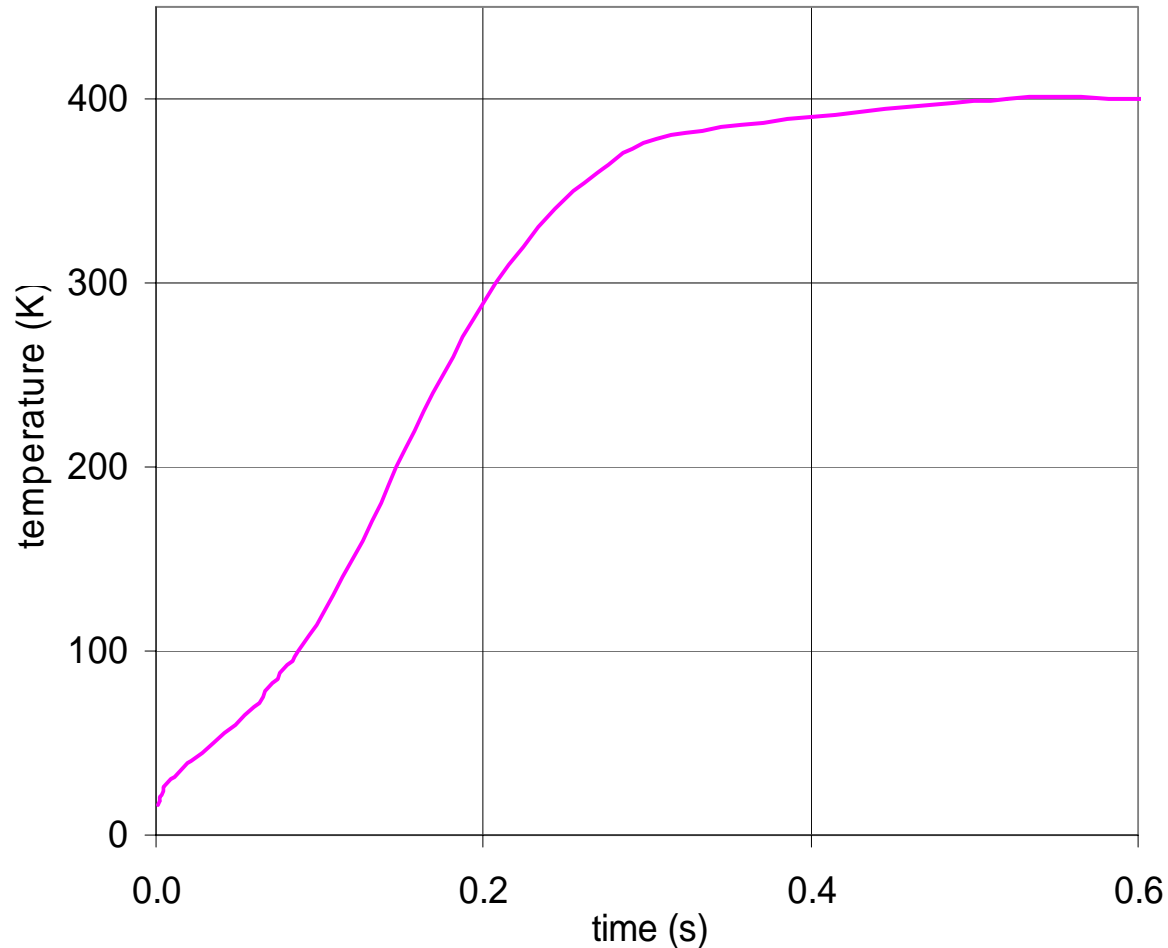
*Dipole GSI001 measured at Brookhaven National Laboratory*

*Superconducting Magnets for Accelerators JUAS Feb 2005*

# Calculating the temperature rise from the current decay curve

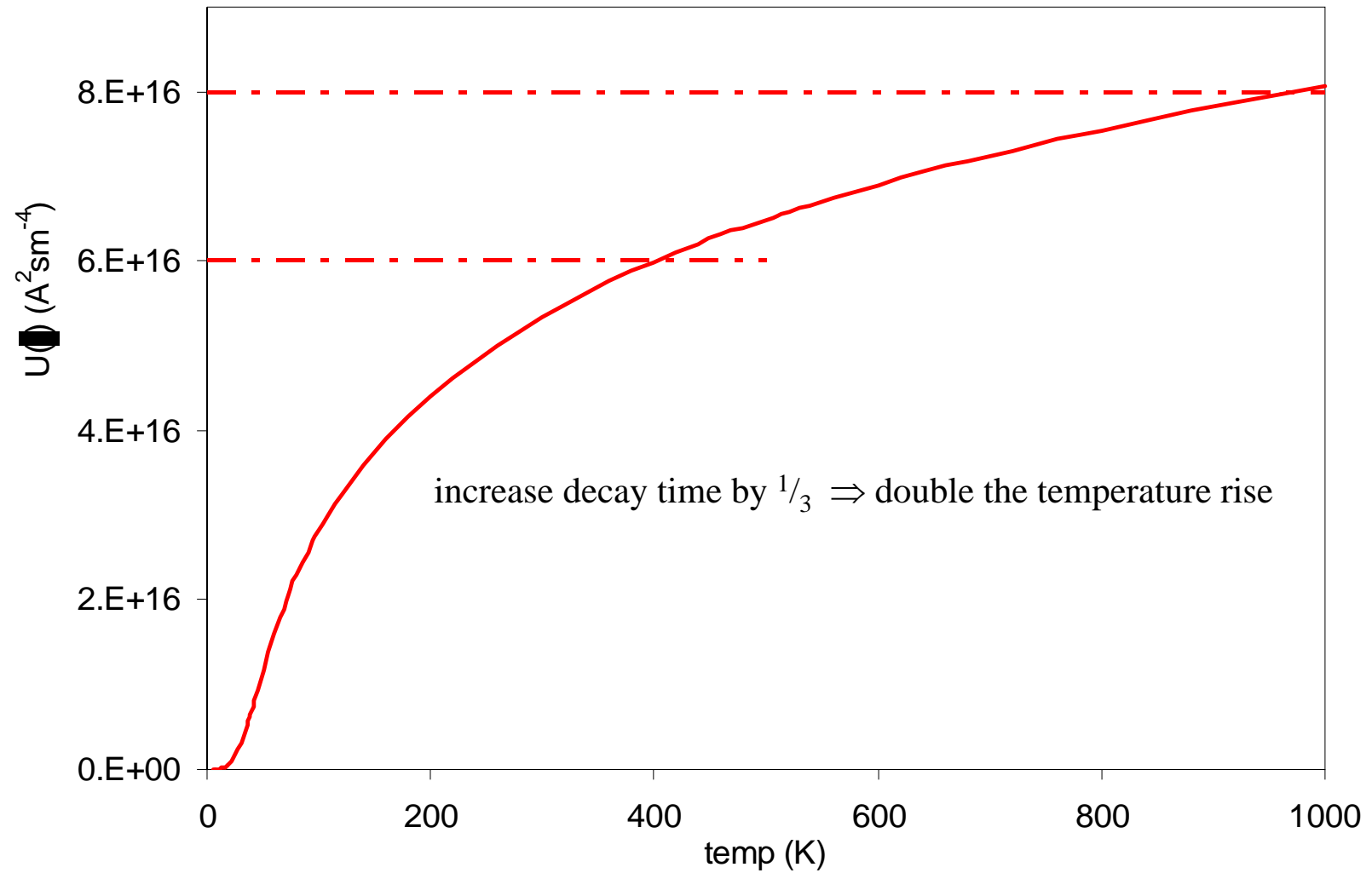


# Calculated temperature

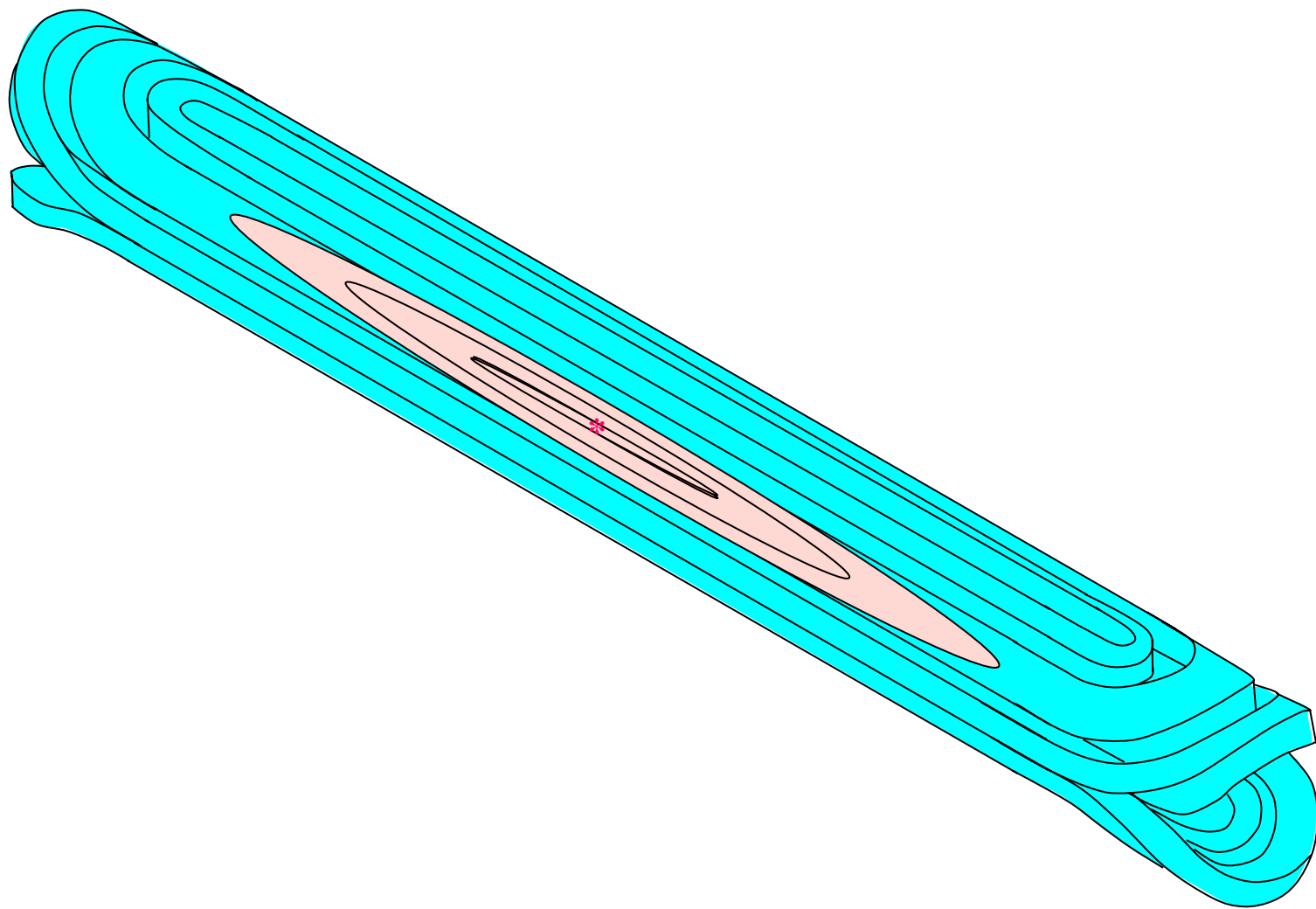


- calculate the  $U(\theta)$  function from known materials properties
- measure the current decay profile
- calculate the maximum temperature rise at the point where quench starts
- we now know if the temperature rise is acceptable  
- but only after it has happened!
- need to calculate current decay curve before quenching

# *Sensitivity of temperature rise*

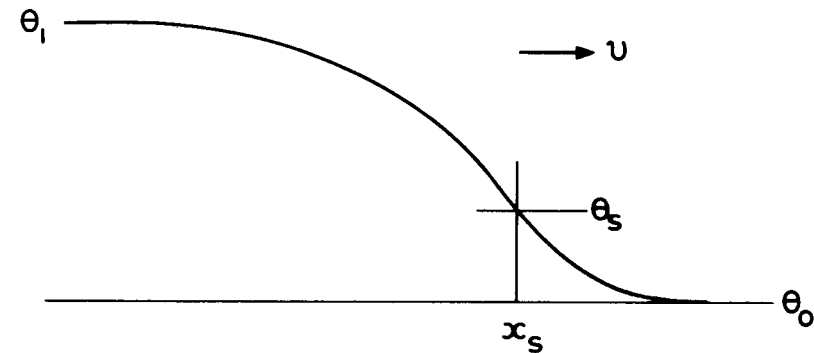






# Quench propagation velocity 1

- resistive zone starts at a point and spreads outwards
- the force driving it forward is the heat generation in the normal zone, together with heat conduction along the wire
- write the heat conduction equations with resistive power generation  $G$  per unit volume in left hand region and  $G = 0$  in right hand region.



$$\frac{\partial}{\partial x} \left( kA \frac{\partial \theta}{\partial x} \right) - \gamma CA \frac{\partial \theta}{\partial t} - hP(\theta - \theta_0) + GA = 0$$

where  $P$  = cooled perimeter,  $A$  = area of cross section,  $k$  = thermal conductivity,  $h$  = heat transfer coefficient,  $C$  = specific heat,  $\gamma$  = density

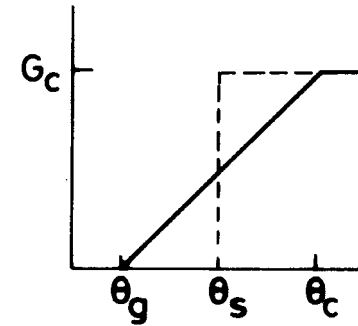
assume  $x_s$  moves to the right at velocity  $v$  and take a new coordinate  $\varepsilon = x - x_s = x - vt$

$$\frac{d^2 \theta}{d\varepsilon^2} + \frac{v\gamma C}{k} \frac{d\theta}{d\varepsilon} - \frac{hP}{kA} (\theta - \theta_0) + \frac{G}{k} = 0$$

# Quench propagation velocity 2

$$\frac{d^2\theta}{d\varepsilon^2} + \frac{v\gamma C}{k} \frac{d\theta}{d\varepsilon} - \frac{hP}{kA} (\theta - \theta_0) + \frac{G}{k} = 0$$

we approximate to a sharp transition between superconductivity and resistance at  $\theta_s$ , although in copper composites it is a progressive current transfer



when  $h = 0$ , the solution for  $\theta$  which gives a continuous join between left and right sides gives the **adiabatic propagation velocity**

$$v_{ad} = \frac{J}{\gamma C} \left\{ \frac{\rho k}{\theta_s - \theta_0} \right\}^{\frac{1}{2}} = \frac{J}{\gamma C} \left\{ \frac{L_o \theta_s}{\theta_s - \theta_0} \right\}^{\frac{1}{2}}$$

recap Wiedemann Franz Law  
 $\rho(\theta) \cdot k(\theta) = L_o \theta$

because C varies so strongly with temperature, it is better to calculate an average C from the enthalpy change

$$C_{av}(\theta_o, \theta_c) = \frac{H(\theta_c) - H(\theta_o)}{(\theta_c - \theta_o)}$$

the resistive zone also propagates sideways through the inter-turn insulation; calculation is similar, but with a lower thermal conductivity and (possibly) a higher specific heat - thus the velocity ratio  $\alpha$  is:

$$\alpha = \frac{v_{trans}}{v_{long}} = \frac{\gamma C_{long}}{\gamma C_{trans}} \left\{ \frac{k_{trans}}{k_{long}} \right\}^{\frac{1}{2}}$$

# Resistance growth and current decay 1

Approximate theory based on some simplifying assumptions:

a) current remains constant at its starting value until all the inductive stored energy of the magnet has been dissipated, then it falls to zero

b) temperature rises given by the parabolic  $U(\theta)$  approximation, define  $U_1$  at  $\theta_1$

$$\int J^2 dt = J_o^2 T_d = U(\theta) \cong U_1 (\theta / \theta_1)^{1/2}$$

c) resistivity increases linearly with temperature

after time  $T$  the resistive zone has grown to an ellipse of semi axis  $x = vt$  and ellipticity  $\alpha$

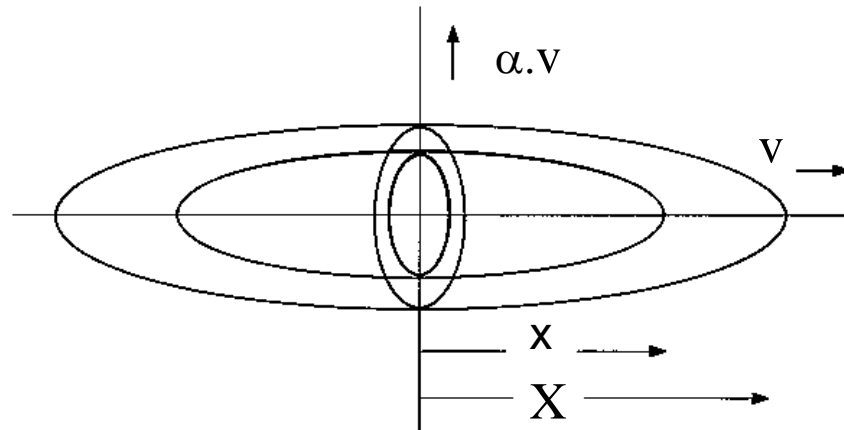
resistance of the zone

$$R = \int_0^X \frac{4\pi x^2 \alpha^2 \rho(\theta)}{A^2} dx$$

substitute

$$\rho(\theta) = \rho_1 \left( \frac{\theta}{\theta_1} \right) = \rho_1 \left( \frac{U}{U_1} \right)^2 = \rho_1 \frac{J_o^4 \tau^2}{U_1^2}$$

where  $\tau$  is the elapsed time since normality:  
at the centre  $\tau = T$ , at the edge  $t = 0$   
and in between  $\tau = T - x/v$



## Resistance growth and current decay 2

$$R = \int_0^{vT} \frac{4\pi x^2 \alpha^2 \rho_1 J_o^4 \left(T - \frac{x}{v}\right)^2}{A^2 U_1^2} dx = \frac{4\pi \rho_1 \alpha^2 J_o^4 v^3 T^5}{30 A^2 U_1^2} \quad \text{recap } \tau \text{ is the elapsed time since normality:}$$

where:  $v$  = longitudinal velocity,  $\alpha$  = ratio longitudinal/transverse velocity,  $\rho_1$  = resistivity at  $\theta_1$ ,  $U_1 = U$  function at  $\theta_1$ ,  $J_o$  = current density at start

- characteristic time  $T_Q$  of current decay is obtained by setting energy dissipated in the normal region equal to the initial stored energy  $E$  (assuming  $I = I_o$  is constant throughout)

$$\int_0^{T_Q} I^2 R(T) dT = E$$

$$\int_0^{T_Q} J_o^2 A^2 \frac{4\pi \rho_1 \alpha^2 J_o^4 v^3 T^5}{30 A^2 U_1^2} dt = E$$

thus

$$T_Q = \frac{1}{J_o} \left\{ \frac{45 U_1^2 E}{\pi \rho_1 \alpha^2 v^3} \right\}^{\frac{1}{6}}$$

characteristic decay time of the quench

**Health Warning:** this rough model ignores what happens when normal zone reaches coil boundaries (extends  $\tau$ ) – for a good answer use the computer!

# Resistance growth and current decay 3

maximum temperature  
(at centre of normal  
zone) from

$$J_o^2 T_Q = U(\theta)$$

with the  
parabolic  
approximation

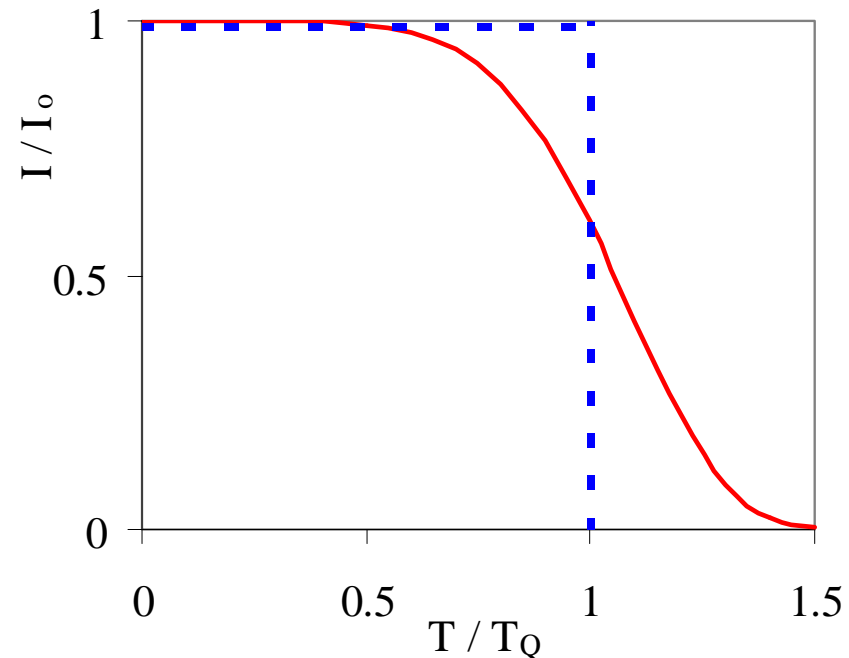
$$\theta_m = \frac{J_o^4 T_Q^2 \theta_1}{U_1^2}$$

substitute back to get  
the current decay curve

$$I(t) = I_o e^{-\frac{T^6}{2T_Q^6}} = I_o e^{-t^6/2}$$

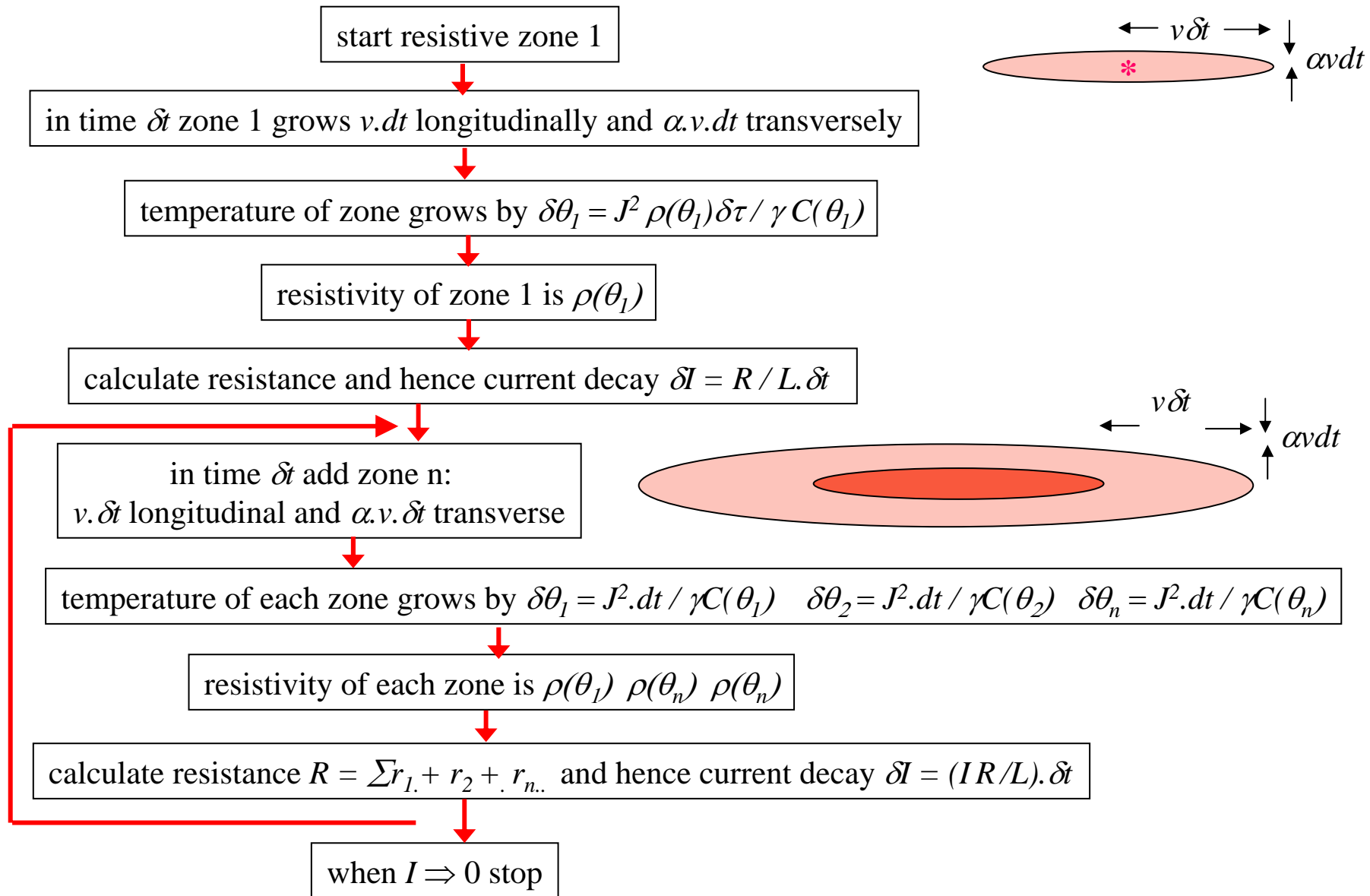
where  $t = T/T_Q$

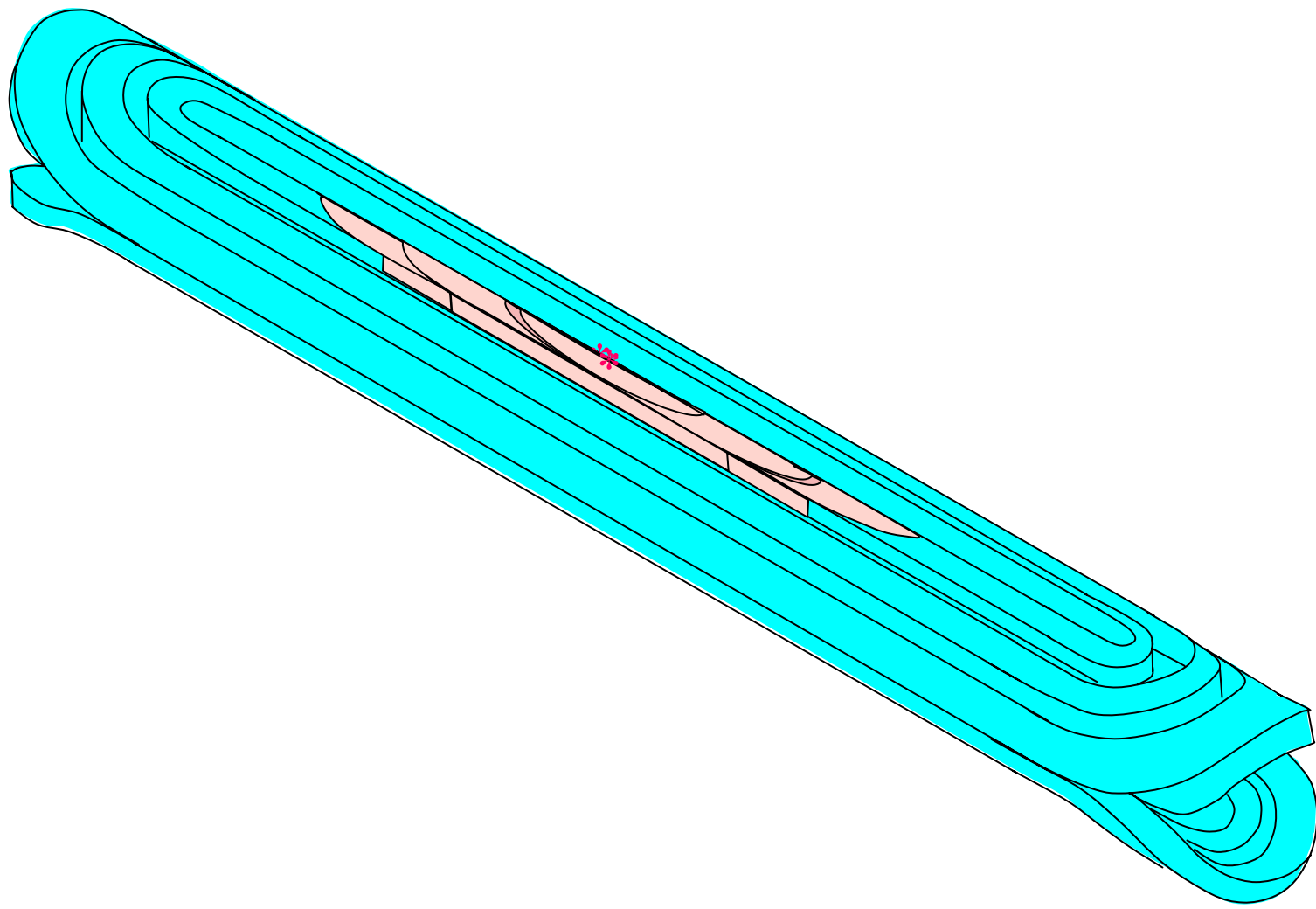
*perhaps the original  
approximation (a) wasn't so  
bad after all!*



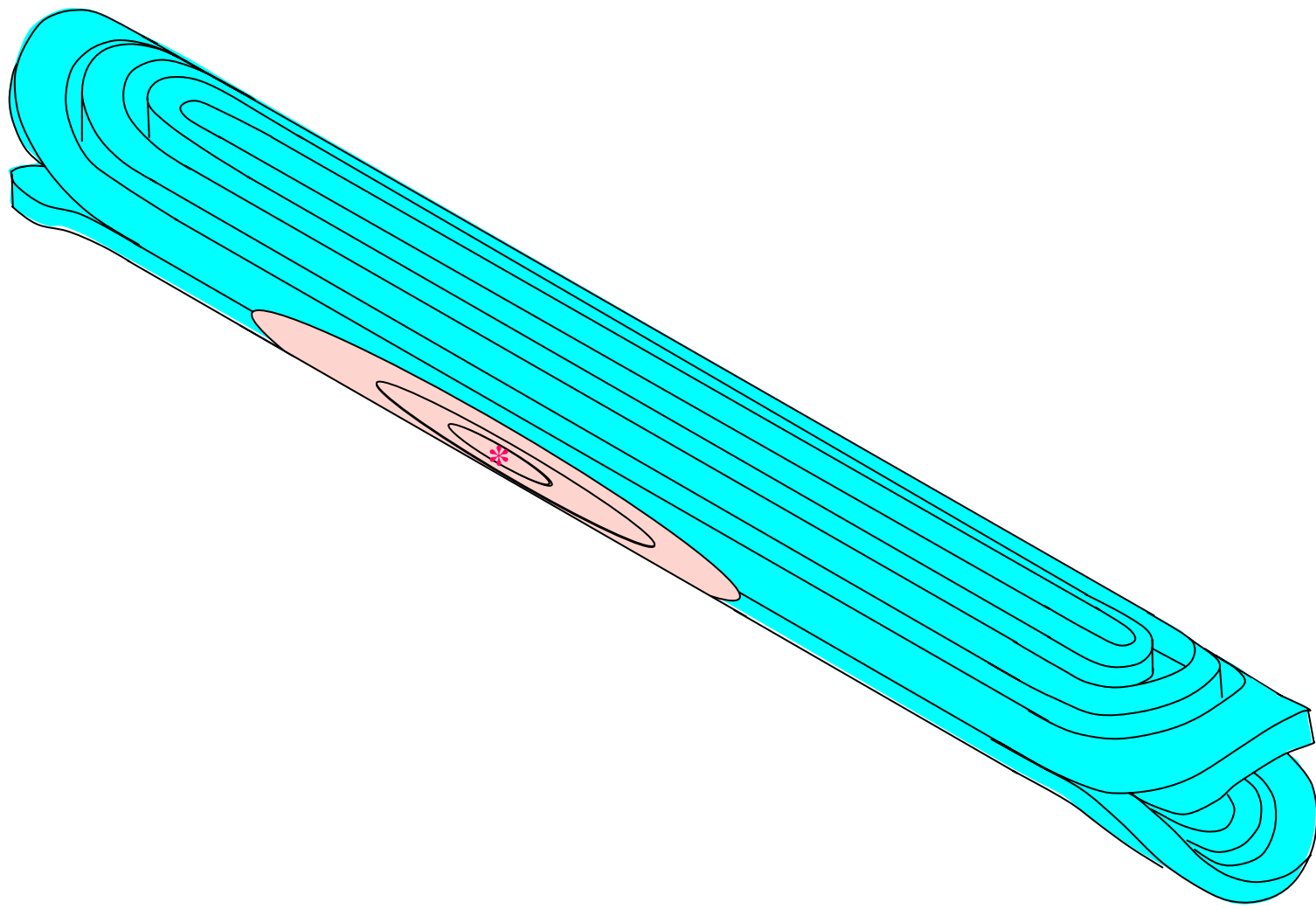
**Health Warning:** this rough model ignores what happens when normal zone reaches coil boundaries (extends  $\tau$ ) – for a good answer use the computer!

# Computation of resistance growth and current decay

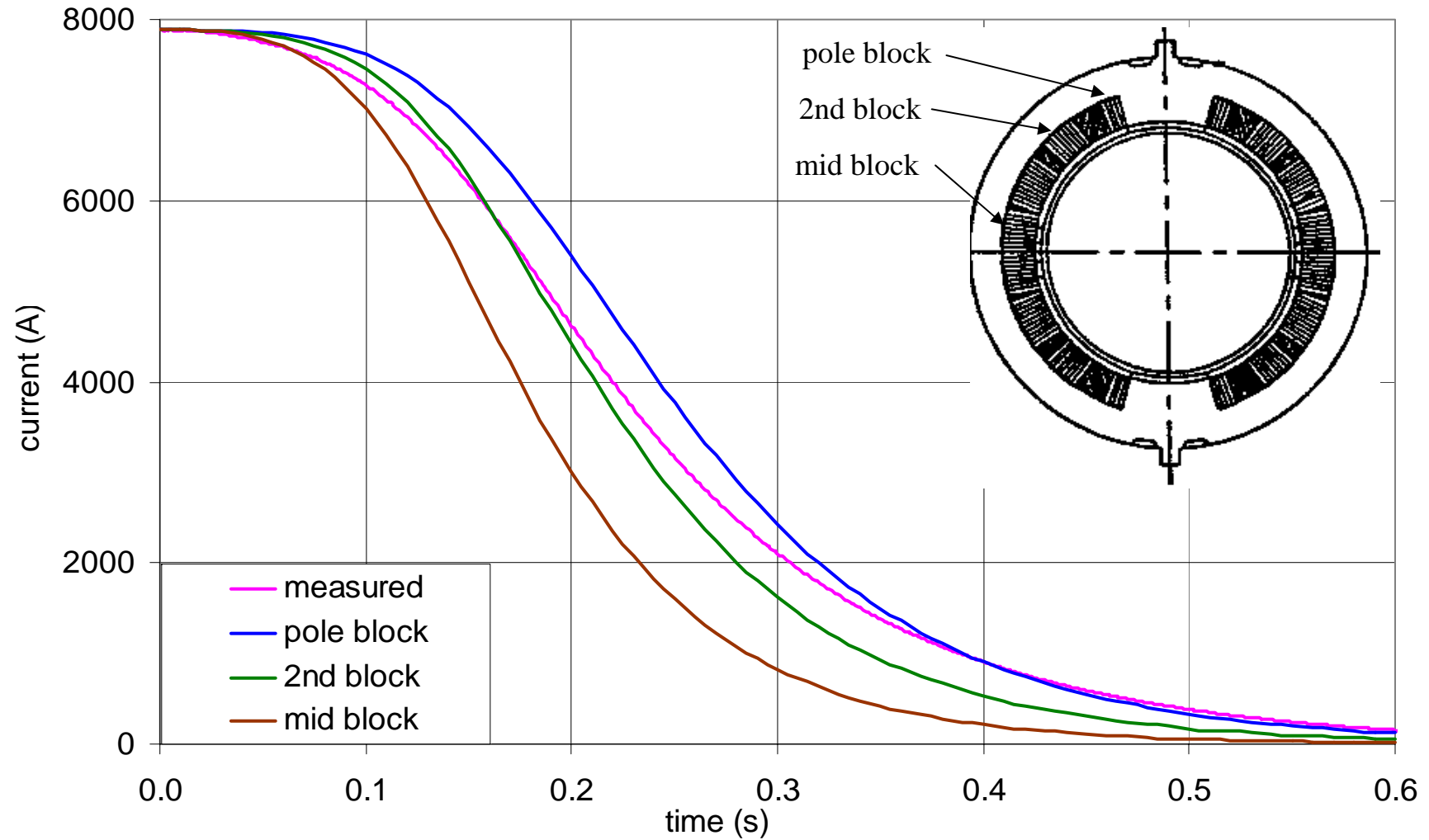




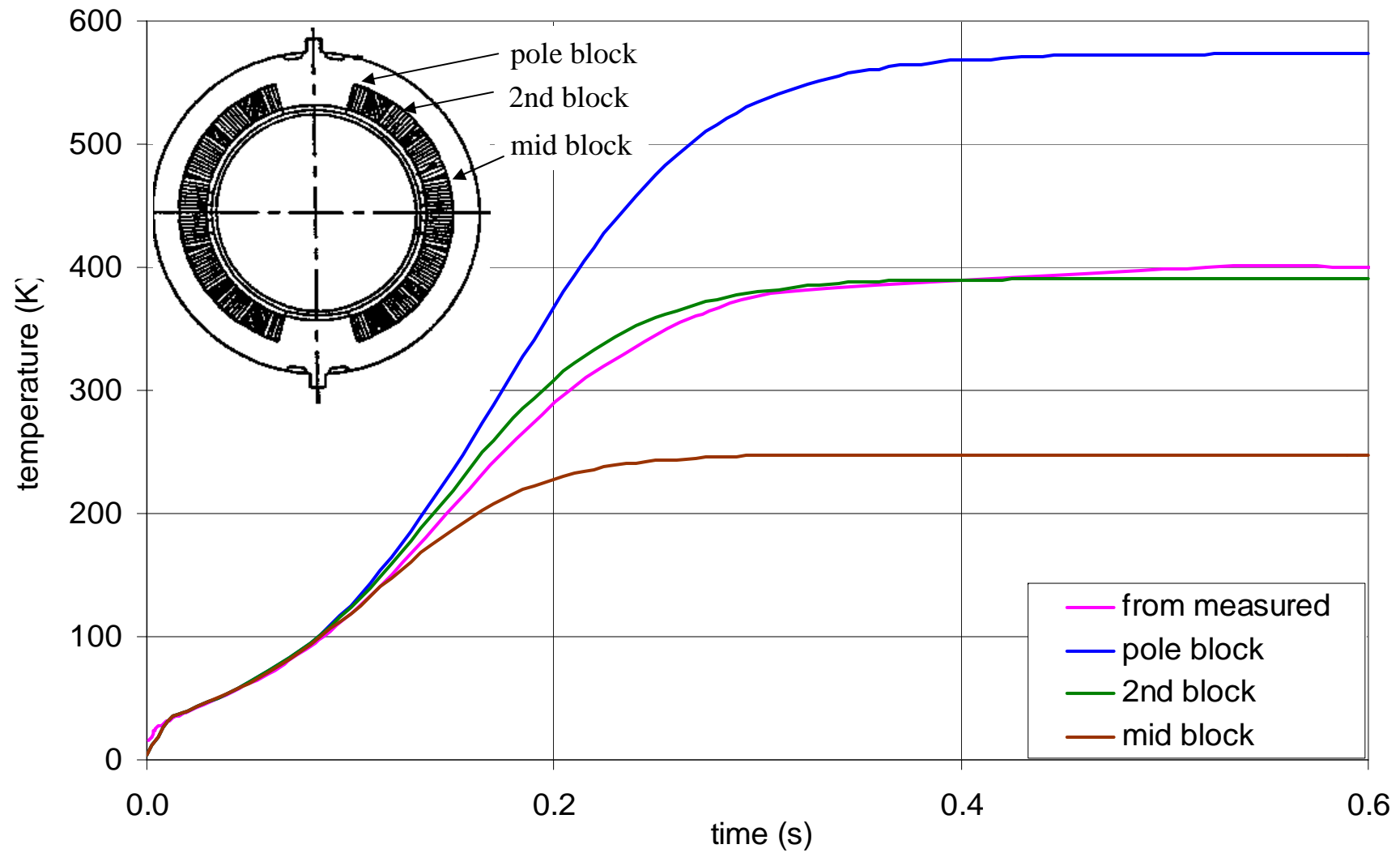




# Computer simulation of quench (dipole GSI001)

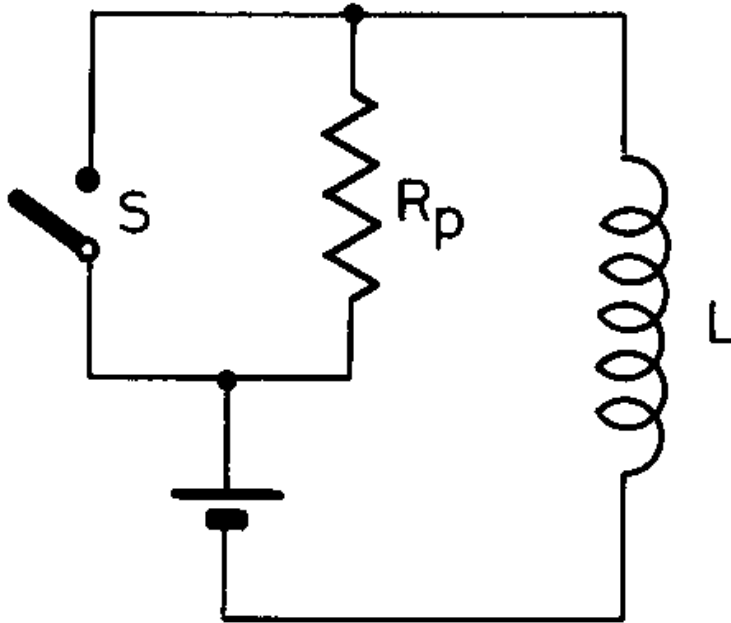


# Computer simulation of quench temperature rise



## Methods of quench protection:

### 1) external dump resistor



- detect the quench electronically
- open an external circuit breaker
- force the current to decay with a time constant

$$I = I_o e^{-\frac{t}{\tau}} \quad \text{where} \quad \tau = \frac{L}{R_p}$$

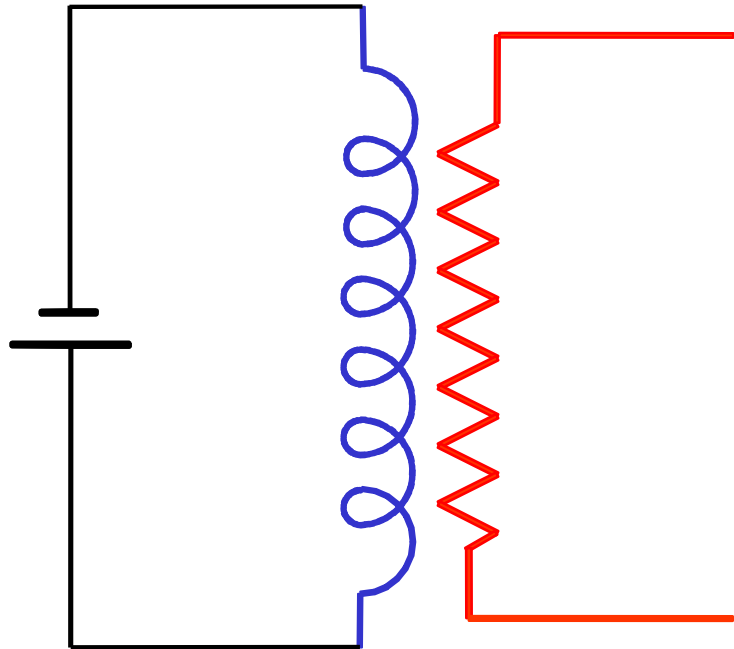
- calculate  $\theta_{\max}$  from

$$J_o^2 \tau = U(\theta_m)$$

*Note: circuit breaker must be able to open at full current against a voltage  $V = I \cdot R_p$  (expensive)*

## Methods of quench protection:

### 2) quench back heater



- detect the quench electronically
- power a heater in good thermal contact with the winding
- this quenches other regions of the magnet, effectively forcing the normal zone to grow more rapidly
  - ⇒ higher resistance
  - ⇒ shorter decay time
  - ⇒ lower temperature rise at the hot spot

*Note: usually pulse the heater by a capacitor, the high voltages involved raise a conflict between:-*

- *good thermal contact*
- *good electrical insulation*

*method most commonly used in accelerator magnets ✓*

# Methods of quench protection:

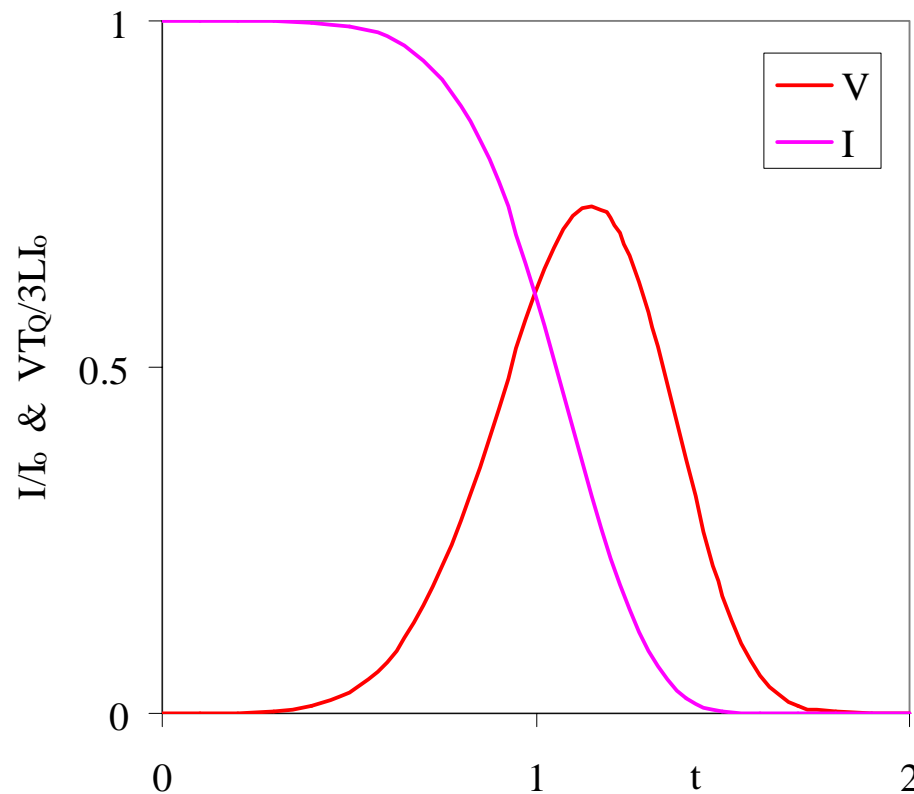
## 3) quench detection

recap  
current  
decay

$$I = I_0 e^{-T^6/2T_Q^6} = I_0 e^{-t^6/2}$$

internal  
voltage

$$V = -L \frac{dI}{dt} = \frac{3LI_0}{T_Q} \left( \frac{T}{T_Q} \right)^5 e^{-T^6/2T_Q^6} = \frac{3LI_0}{T_Q} t^5 e^{-t^6/2}$$

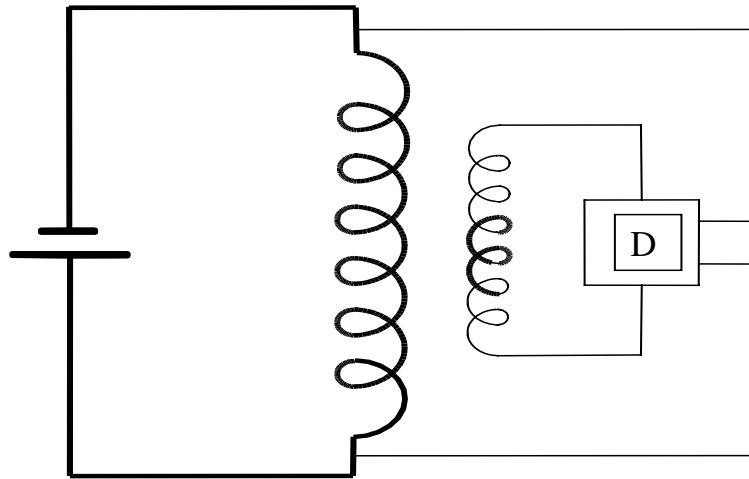


- not much happens in the early stages  
- small  $dI/dt \Rightarrow$  small  $V$
- but important to act soon if we are to reduce  $T_Q$  significantly
- so must detect small voltage
- superconducting magnets have large inductance  $\Rightarrow$  large voltages during charging
- detector must reject  $V = L dI/dt$  and pick up  $V = IR$
- detector must also withstand high voltage - **as must the insulation**

## Methods of quench protection:

### 3) quench detection

#### i) Mutual inductance



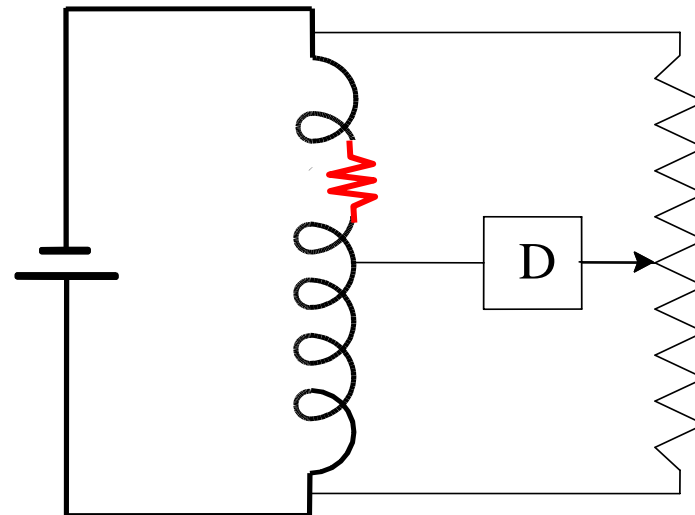
detector subtracts voltages to give

$$V = L \frac{di}{dt} + IR_Q - M \frac{di}{dt}$$

- adjust detector to effectively make  $L = M$
- $M$  can be a toroid linking the current supply bus, but must be linear - no iron!

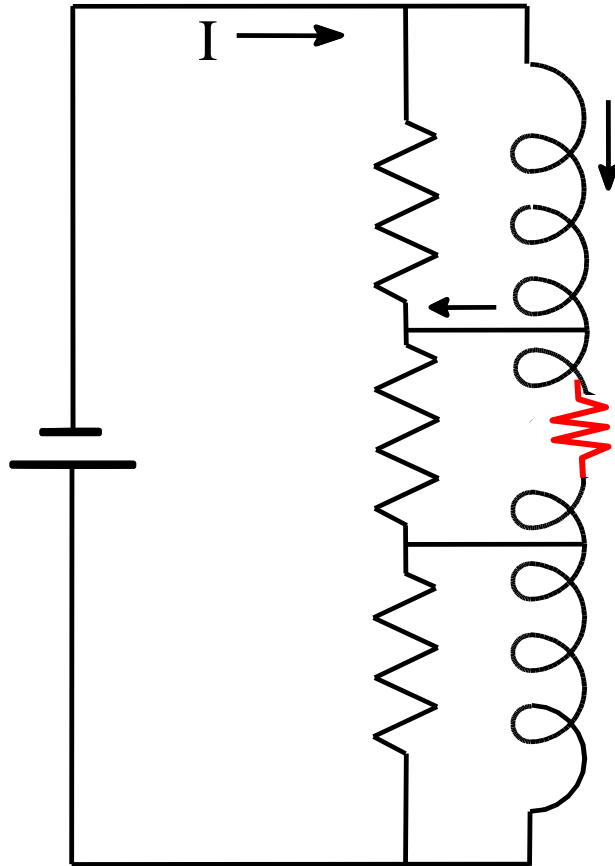
#### ii) Balanced potentiometer

- adjust for balance when not quenched
- unbalance of resistive zone seen as voltage across detector D
- if you worry about symmetrical quenches connect a second detector at a different point

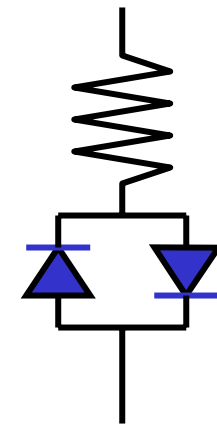


## Methods of quench protection:

### 4) Subdivision



- resistor chain across magnet - cold in cryostat
- current from rest of magnet can by-pass the resistive section
- effective inductance of the quenched section is reduced
  - ⇒ reduced decay time
  - ⇒ reduced temperature rise
- current in rest of magnet increased by mutual inductance effects
  - ⇒ quench initiation in other regions
- often use cold diodes to avoid shunting magnet when charging it
- diodes only conduct (forwards) when voltage rises to quench levels
- connect diodes 'back to back' so they can conduct (above threshold) in either direction





# Case study: LHC dipole protection

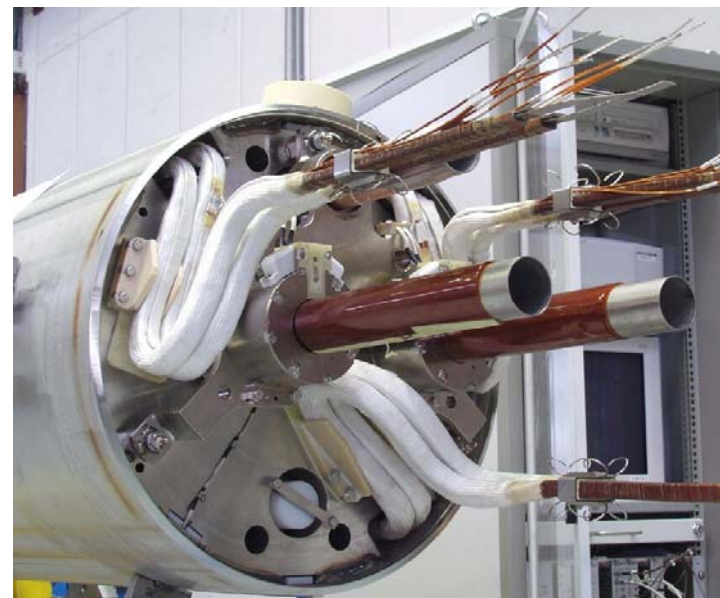
**It's difficult! - the main challenges are:**

## 1) Series connection of many magnets

- In each octant, 154 dipoles are connected in series. If one magnet quenches, the combined inductance of the others will try to maintain the current. Result is that the stored energy of all 154 magnets will be fed into the magnet which has quenched  $\Rightarrow$  vaporization of that magnet!.
- **Solution 1:** put cold diodes across the terminals of each magnet. In normal operation, the diodes do not conduct - so that the magnets all track accurately. At quench, the diodes of the quenched magnet conduct so that the octant current by-passes that magnet.
- **Solution 2:** open a circuit breaker onto a dump resistor (several tonnes) so that the current in the octant is reduced to zero in  $\sim 100$  secs.

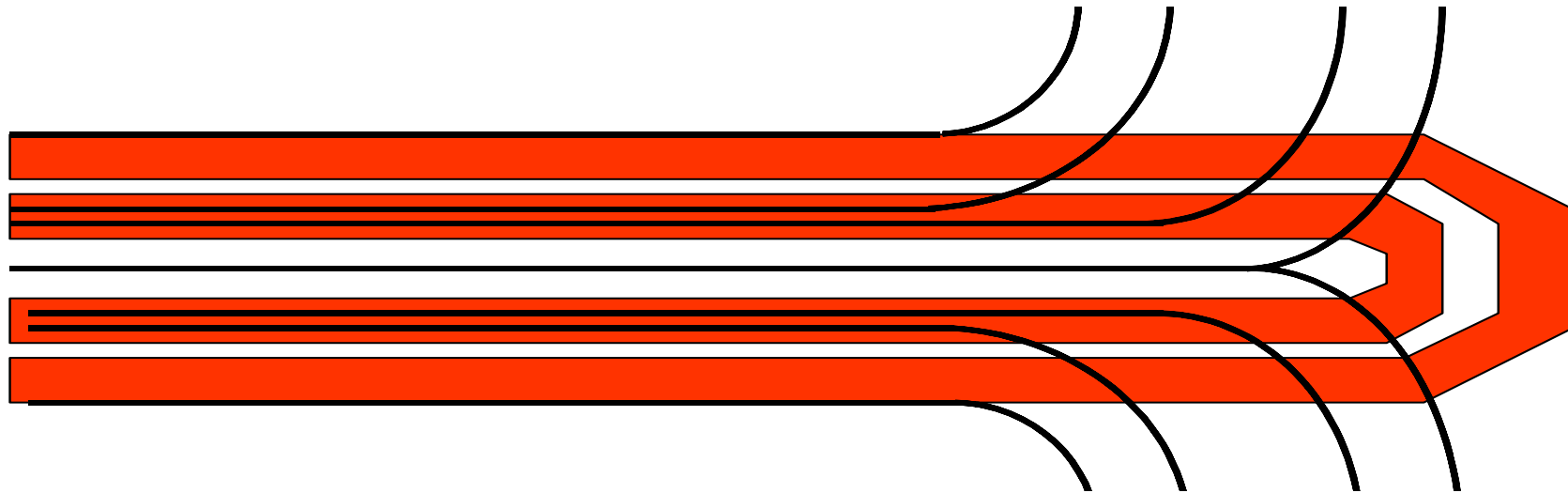
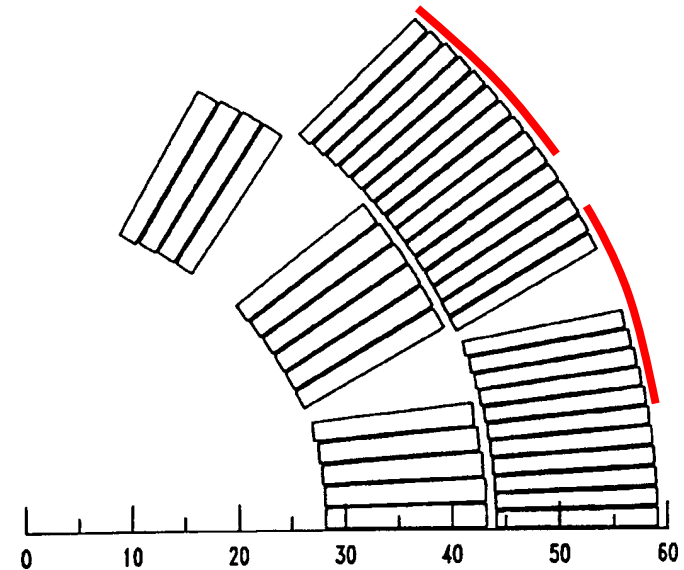
## 2) High current density, high stored energy and long length

- As a result of these factors, the individual magnets are not self protecting. If they were to quench alone or with the by-pass diode, they would still burn out.
- **Solution 3:** Quench heaters on top and bottom halves of every magnet.

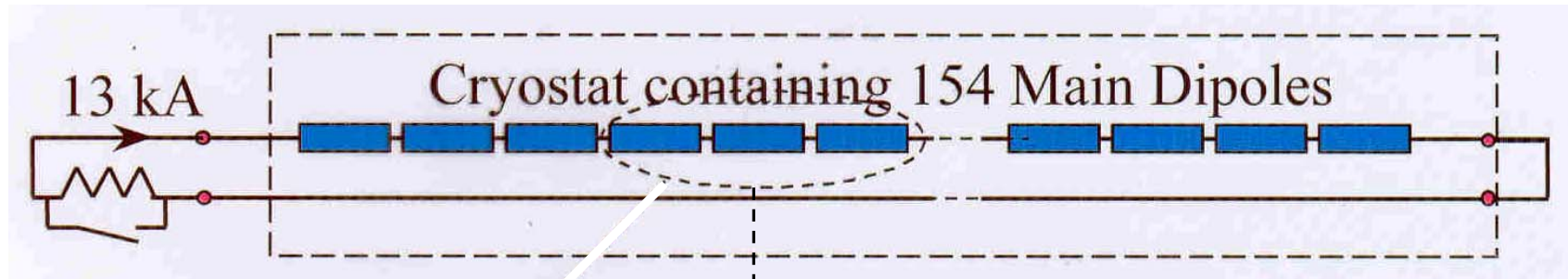


# LHC quench-back heaters

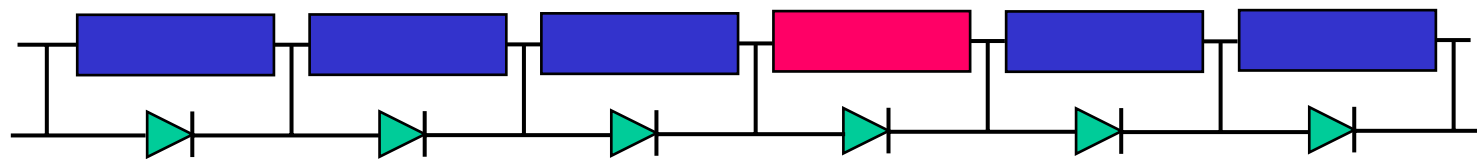
- stainless steel foil 15mm x 25  $\mu\text{m}$  glued to outer surface of winding
- insulated by Kapton
- pulsed by capacitor 2 x 3.3 mF at 400 V = 500 J
- quench delay
  - at rated current = 30msec
  - at 60% of rated current = 50msec
- copper plated 'stripes' to reduce resistance



# *LHC power supply circuit for one octant*



circuit  
breaker



- diodes allow the octant current to by-pass the magnet which has quenched
- circuit breaker reduces to octant current to zero with a time constant of 100 sec
- initial voltage across breaker = 2000V
- stored energy of the octant = 1.33GJ

# *Diodes to by-pass the main ring current*

Installing the cold diode package on the end of an LHC dipole



# Quenching: concluding remarks

- magnets store large amounts of energy - during a quench this energy gets dumped in the winding
  - ⇒ intense heating ( $J \sim$  fuse blowing)
  - ⇒ possible death of magnet
- temperature rise and internal voltage can be calculated from the current decay time
- simple analytic model gives rough decay time but ignores boundaries
- computer modelling of the quench process gives a good estimate of decay time
  - but must decide where the quench starts
- if temperature rise is too much, must use a protection scheme
- active quench protection schemes use quench heaters or an external circuit breaker
  - need a quench detection circuit which must reject  $LdI/dt$  and be **100% reliable**
- passive quench protection schemes are less effective because  $V$  grows so slowly
  - but are 100% reliable
- protection of accelerator magnets is made more difficult by series connection
  - all the other magnets feed their energy into the one that quenches
- for accelerator magnets use by-pass diodes and quench heaters
- remember the quench when designing the electrical insulation

**always do the quench calculations before testing the magnet ✓**